solved, but can you not give the faint polar regions more exposure than the bright equatorial streamers?" This can be done by placing somewhere between the source of power for driving the diaphragm and the diaphragm itself, two or more elliptical gear-wheels, which can be made to give a variable motion, giving the polar region from a small fraction to many times more exposure than that received by the equatorial parts. Another friend believes this ought not to be done, as we *want* this difference to show upon the plate.

I constructed a model, giving the polar regions twice the exposure received by the equator (in the same zones) and it is entirely reliable, but I do not expect to employ this feature at the coming eclipse. Finally, it should be said that my experiments have been conducted at the expense of a fund placed at the disposition of the LICK Observatory by Mrs. PHEBE HEARST, a member of this society.

CHABOT OBSERVATORY, Oakland, Cal., June, 1895.

A STUDY OF THE PHYSICAL CHARACTERISTICS OF COMET RORDAME.

By W. J. HUSSEY.

On the evening of July 8, 1893, Mr. ALFRED RORDAME, an amateur astronomer residing in Salt Lake City, discovered a bright comet in the constellation *Lynx*. He at once reported his discovery to the WARNER Observatory, and within a day or two the news had been communicated to astronomers throughout the world. The comet was discovered independently about the same time in many places. It had also been seen previously as a "hazy star," and even in the preceding month it had been observed by an amateur astronomer, who mistook it for another comet, already known.

For nearly two weeks it was a conspicuous object in the western sky during the early portion of the night. It was then at its greatest brilliancy, and, in most respects, in a very favorable situation for observation. It was near the Earth and near the Sun. On the day of its discovery it passed the point in its orbit nearest the Earth, at a distance of about 38,000,000 miles. On

the preceding day it had passed perihelion at a distance of 62,700,000 miles from the Sun. Its motion was retrograde, the plane of its orbit being inclined 159° 58′ to the plane of the ecliptic. The circumstances of its motion were such that shortly after perihelion passage it and the Earth were moving nearly in opposite directions. In consequence of this, its distance increased rapidly. In ten days (July 18th) it had become 58,000,000, and in a month (August 8th), 130,000,000 miles. Its light also decreased rapidly. On the 8th of August its theoretical brightness was only one twenty-fifth as great as at the time of its discovery, and very few observations were made after this time.

For a few days after the discovery the tail was bright, and, under the most favorable atmospheric conditions, could be traced more than twelve degrees with the naked eye. Moreover, it passed rapidly toward the position in which it could be observed in its true proportions. On July 11th (18^h G. M. T.) the angle between the line of sight and a line drawn through the Sun and comet was, approximately, 50°. The tail was then foreshortened by projection about twenty-three per cent. A week later the angle had increased to 82°, and the tail was then foreshortened only one per cent. On July 20th the tail was perpendicular to the line of sight, and it was then seen in its true length.

The Moon was absent when the comet was discovered. New Moon occurred on July 13th, but it was not until five days later that its light produced sufficient illumination of the sky to affect the photographic work which was being done. The absence of the Moon at this critical time, during which the comet was in the most favorable position for observation and at its greatest brilliancy, was a most fortunate circumstance.

During June and July, 1893, I was photographing various celestial objects — nebulæ, the *Milky Way*, etc., with the CROCKER telescope of the LICK Observatory. The appearance of the comet enabled me to obtain a valuable series of photographs of it, which I have recently examined with greater care than I was able to do at the time they were taken.

The CROCKER telescope is provided with a large portrait lens (WILLARD lens), having an aperture nearly six inches in diameter, and with an equivalent focal length of 30.82 inches. The negatives obtained with this telescope have, therefore, a scale of $1° = 0.538$ inches, or, 1 inch $= 1°.86$. The use of such lenses in astronomical photography is too well known to require any

comment. Their short focal length and great light power render them especially suitable for photographing faint, extended objects, such as comets, large nebulæ, and the *Milky Way*.

Thirteen photographs of the comet were secured — eleven with the CROCKER telescope, and two with a small camera having a lens about an inch and a quarter in diameter, and an equivalent focal length of about eleven inches. Six of the photographs are very good. They were obtained with exposures ranging from an hour to an hour and twenty minutes in length. They were taken to obtain as complete pictures of the comet as possible, in the time that it remained sufficiently above the horizon after dark to be successfully photographed. Three short exposures of six and eight minutes were made to form an idea of the photographic intensity of the comet's light, and to obtain evidences of rapid changes of form in the structure of the comet itself. Considering the shortness of these exposures, the results are very good. One of them has been particularly valuable in enabling the velocity to be determined with which the matter composing the tail was receding from the head. The two other photographs, obtained with the CROCKER telescope, are the results of the first night's work, July 11th. They were the least successful of all the photographs. The first plate used was defective and comparatively slow, and the exposure was cut short at the end of twenty minutes by the view in the finder being obstructed by the lower part of the slit of the dome. The finder was on the lower side of the telescope, for that position, and at some distance from it. Had the difficulty been foreseen, and the finder placed on the opposite side of the telescope, as was done the next night, the exposure might have been continued three-quarters of an hour longer, and another good photograph obtained. The plates were changed, and an exposure of forty-five minutes made, with no attempt to correct the motion of the telescope for the proper motion of the comet. The result was a comet-trail possessing considerable interest.

On two occasions a small camera ($6\frac{1}{2} \times 8\frac{1}{2}$) properly focused was removed from its tripod and secured to the telescope by means of a strong cord. Exposures with it and the telescope were then made at the same time. One of these photographs is particularly interesting in showing what can be done with a small lens, an inch and a quarter in diameter. An exposure of seventy minutes gave a negative having sufficient density to enable prints

to be made from it, showing fully twelve degrees of the tail of the comet, with its principal peculiarities, and the trails of more than 500 stars. The stars photograph very quickly, even with very small apertures. In the course of some experiments on reduced apertures, I found that with the aperture of the CROCKER telescope reduced to a central circular area of one-fourth of a square inch, *Polaris* was distinctly photographed with an exposure of less than four seconds. An exposure of two seconds was not sufficient to give a developable image.

A few of the plates used in photographing the comet were SEED 26 x. Most of them, however, were coated with an unusually sensitive emulsion by CRAMER, Emulsion 6715. In photographing other objects,— the *Andromeda Nebula*, for example,— the results obtained with these plates showed them to be more than twice as rapid as the SEED 26 x plates. The success of my photographs of the comet, and especially of the short exposures, is largely due to this.

The sensitiveness of these plates stands in marked contrast to those which were used in the early attempts to photograph comets. In 1874 COGGIA'S comet was very bright, but the attempts to photograph it were not attended with success. In consequence of this, the comet's light was said to possess but little photographic intensity; in reality the plates were slow.

The principal comet of 1881 (Comet 1881, III), discovered by Mr. TEBBUTT, of New South Wales, was also very bright, and is distinguished in being the first comet to have not only its form but also its spectrum photographed. Dr. DRAPER, of New York, with an exposure of two hours and forty-two minutes, obtained a negative showing the head of the comet, about ten degrees of its tail, and the trails of many stars. A few days later he photographed its spectrum. In this he had been anticipated by Dr. HUGGINS, in England, who obtained a photograph of the comet's spectrum on June 24, 1881, the same evening that Dr. DRAPER had secured his first, not best, photograph of the comet itself. At Paris, M. JANSSEN was also at work about the same time, and he succeeded in obtaining a photograph showing the head and about two degrees of the tail.

Still more successful were the photographs of the Great Comet which appeared in 1882. At the Royal Observatory at the Cape of Good Hope, a camera provided with a large portrait lens was strapped to a telescope and a number of good photographs

obtained of this, the most magnificent comet which has appeared during the last third of a century, its last splendid predecessor being the great comet of DONATI, in 1858. Magnificent as it was, it did not receive from photographers the attention it deserved, which, of course, is not very surprising, for astronomical photography was then in its infancy. The next ten years, however, were ones of great progress in this line of astronomical work. The modern dry plate was improved and brought to a high degree of perfection; telescopes designed especially for photography were constructed, and others remodeled, so as to enable them to do this kind of work. At present the photographic equipment in the hands of astronomers is very extensive, and if another comet were to appear like the great one of 1882, or, very much better, like that of DONATI in 1858,—for the latter was in a better situation for observation,—it would be photographed hundreds and perhaps thousands of times, and the photographs obtained would afford a larger amount of accurate data for the study of *certain* kinds of cometary phenomena than has been obtained visually from all the comets of the past.

Visual observations have shown that many comets have undergone very considerable changes of form in short periods of time. Such changes have, naturally enough, been more frequently noted and have excited greater attention and comment in the case of great comets than in small ones. As long as the information concerning these changes depended solely on the more or less uncertain visual impressions of the observers, and on the necessarily imperfect sketches made by them, there were often good reasons for doubting the correctness of the observations, so far, at least, as concerned the less conspicuous changes. But the changes which have been observed visually do not compare with those which have been revealed by photography, and of the reality of the latter there can be no question. Even the comparatively small comets of recent years, notably that discovered by SWIFT in 1892, those by RORDAME and BROOKS in 1893, and that by GALE in 1894, have furnished photographs showing the most marked differences from day to day, and differences, too, which were not detected visually.

It is to be noted, however, that many of the changes which have been best observed visually have related to nuclei, envelopes, luminous sectors, and other phenomena connected with the heads of the great comets; whereas, those best observed photographically

have related more particularly to the streamers and condensations composing the tails. No great comet has appeared since photography has reached its present development, and it is not known what results it might afford if properly applied to the heads of such comets. Undoubtedly, exposures made in the right manner would afford much valuable data, but it is hardly probable that it would at once enable visual observations to be entirely dispensed with. The case is, in a way, analagous to that of the planets, where photography has, as yet, been of relatively little real service. It is in regard to the tails of comets that the improved photographic plate has demonstrated its superiority to the eye in dealing with questions relating to structure and changes of form. It can grasp what the eye cannot see. It can picture the comet with more detail and with greater truthfulness and accuracy than any artist.

The photographs of the brighter comets which have appeared during the past three or four years have shown, however capricious cometary forms may have been regarded as a result of visual observations, that they have far less stability than had previously been supposed. The changes which take place have the widest range. They may affect any or all parts of the comet, nucleus, coma, and tail. The nucleus may be sharply defined and starlike, or ill-defined, or even indistinguishable from the coma surrounding it; the coma may change in shape, size, and density; envelopes may be thrown out singly or in complex systems; the tail may consist of a single streamer—at least, apparently so,—or of an indefinite number of them; the streamers composing the tail may leave the coma in a single compressed bundle, or they may spring from it in widely divergent and loosely connected groups; they may be smooth, and straight, and distinct, or they may be lumpy, crooked, interlacing, and spirally twisted; or again, they may be broken into fragments, and scattered as though they were as smoke and driven by the wind. The appearance one day affords no indication as to what it may be the next. Conditions and appearances seem to change incessantly. The most radical changes of form have been observed in almost every reasonably bright comet that has been photographed. The changes sometimes take place so rapidly as to become conspicuous in an hour or two. We shall, further on, speak of such a change in the case of RORDAME'S comet, and of some considerations which are suggested by it.

COMET RORDAME, JULY 13, 1893.
$9^h\ 10^m - 10^h\ 20^m$ P. S. T.
Photographed by W. J. HUSSEY, at the LICK Observatory.

THE NUCLEUS AND COMA OF COMET RÖRDAME.

In the earlier photographs of this comet the nucleus was bright and distinct. It also appeared so in the finder. During the week in which the photographs were taken the coma increased considerably in brightness, and by reason of this the nucleus gradually became obscured. In the later photographs it cannot be seen by examining the negatives with transmitted light. In all cases, however, it can very easily be seen by looking obliquely at the backs of the plates. By reflected light it then presents an appearance very similar to the central point of an over-exposed image of a bright star.

The denser part of the coma was decidedly elliptical in outline during the entire period covered by the photographs — 1893, July 11th to 18th, inclusive. The minor axis was at least approximately coincident with a line drawn through the comet and the Sun. In the reproductions the contrasts are changed to such an extent as to give the coma a very different appearance from that which it has in the original negatives. From measurements of the photographs the following table has been formed, giving

THE DIMENSIONS OF THE DENSER PART OF THE COMA OF RORDAME'S COMET.

DATE, PACIFIC STANDARD TIME.	LENGTH OF EXPOSURE.	MEASURED.		REDUCED.		ECCENTRICITY.
		2*a*	2*b*	2*a*	2*b*	
1893, July $11^d\ 9^h\ 00^m$ — $9^h\ 20^m$	$0^h\ 20^m$	10′.5	8′.4	10′.5	8′.4	.60
12 9 00 — 10 12	1 12	12 .6	10 .4	13 .0	10 .8	.56
13 9 00 — 9 6	0 6	9 .8	8 .8	10 .7	9 .6	.44
13 9 10 — 10 20	1 10	12 .6	11 .1	13 .9	12 .2	.48
14 8 56 — 9 4	0 8	10 .3	8 .6	11 .8	9 .9	.54
14 9 8 — 10 28	1 20	11 .3	9 .6	13 .1	11 .1	.53
15 8 45 — 9 30	0 45	11 .7	10 .0	13 .8	11 .8	.52
16 9 00 — 10 00	1 00	9 .6	8 .5	12 .4	10 .9	.48
18 8 48 — 8 56	0 8	5 .9	5 .1	8 .5	7 .3	.51
18 9 1 — 10 21	1 20	6 .6	5 .8	9 .5	8 .3	.48

In this table the values 2*a*, under the heading "Measured," are the diameters of the coma in a direction perpendicular to the axis of the tail, and the values of 2*b* are those in a direction coincident with it. In the next two columns, under the heading "Reduced," these diameters are given reduced to correspond to to the distance of the comet at the time the first photograph was

taken, July 11th, 9^h 10^m P. S. T. Assuming the outline of the coma to be an ellipse, the next column gives the eccentricity computed from the values $2a$ and $2b$ as axes. The times of beginning and end of the exposures are given under the heading "Date." The positions of the comet at the times the photographs were taken were such that differential refraction shortened the diameters $2b$ more than the corresponding ones, $2a$. This effect of refraction, having a maximum value less than $0'.1$, and being, therefore, considerably less than the uncertainties in the measured diameters, has been neglected in preparing the above table.

It will be noticed that the diameters obtained from the negatives of short exposure are, as might have been expected, materially less than those of long exposure, taken on the same night. From the reduced values, it appears that the dimensions of the coma did not vary much from July 11th to 16th, but that there was a marked decrease between July 16th and 18th. In this interval there was also a marked change in the appearance of the tail near the nucleus. On and preceding July 16th, the tail proceeded from the nucleus in a number of groups of streamers; on July 18th, the streamers formed a single compact bundle at their origin. No photograph was taken on July 17th. On July 18th, the Moon was about five and a half days old, and the illumination of the sky produced by it no doubt tended to extinguish the fainter portions of the outer coma. But, even allowing for this, the change is so considerable that it must be regarded as real.

In some of the other recent comets similar irregular variations have been observed in the diameters of the comas. This was particularly the case with the comets discovered by GALE and HOLMES. In the following table are given the

DIAMETERS OF THE COMA OF GALE'S COMET.

DATE.	DIAMETER OF COMA.	DATE.	DIAMETER OF COMA.
1894, April 5	2′	1894, May 2	12′
23	6	3	18
24	8	5	15
25	10	6	14
26	14	7	13
27	23	8	16
29	15	16	14

These values were published in *Knowledge*, Vol. XVII, page 159, July, 1894. No details are given in connection with them; it is probable that they have not been reduced to a uniform distance. They are the estimates made by Mr. H. C. RUSSELL, Director of the Sydney Observatory. They indicate very large and irregular variations in the diameter of the coma of GALE'S comet, in comparison with which the changes in the dimensions of RORDAME'S comet, while it was under observation, were very slight.

HOLMES' comet is another notable case. Three days after its discovery* it was described by Mr. DENNING† "as a perfectly round mass of nebulosity with a bright central condensation," and with "very definite" edges. While receding from the Earth and from the Sun, it increased in apparent size until its diameter became fully five times as great as at the time of its discovery; at the same time its brightness decreased out of all proportion to the law of inverse squares. Its outline became hazy and indistinct, and a short tail appeared. During the first half of January it continued to grow fainter, and it seemed that it must soon become invisible. On January 16th, however, it was found to have changed suddenly into a bright, hazy, starlike object, having a diameter only one-tenth as great as at the time of discovery. For a few days it remained nearly the same size, but decreased in brightness. It then grew larger and fainter, and finally, in February, disappeared.

In these comets, at least, the changes which took place in the dimensions of the comas were irregular, and did not seem to depend in any way upon the distance from the Sun. This is the more noteworthy in view of the statements to be found in our standard books on astronomy. For example, in YOUNG'S "General Astronomy," an admirable work, page 405, we find the following account:

"It is a very singular fact that the head of a comet continually and regularly changes its diameter as it approaches to and recedes from the Sun; and, what is more singular yet, it *contracts when it approaches the Sun*, instead of expanding, as one would naturally expect it to do under the action of the solar heat. No satisfactory explanation is known. Perhaps the one suggested by Sir JOHN HERSCHEL is as plausible as any,—that the change is optical

* It was discovered November 6, 1892.

† *Astronomy and Astro-Physics*, Vol. XII, page 371.

rather than real; that near the Sun a part of the cometary matter becomes invisible, having been *evaporated*, perhaps, by the solar heat, just as a cloud of fog might be.

"The change is especially conspicuous in ENCKE'S comet. When this body first comes into sight, at a distance of about 130,000,000 miles from the Sun, it has a diameter of nearly 300,000 miles. When it is near perihelion, at a distance from the Sun of only 33,000,000 miles, its diameter shrinks to 12,000 or 14,000 miles, the volume then being less than 1-10,000 of what it was when first seen. As it recedes it expands, and resumes its original dimensions. Other comets show a similar, but usually less striking, change."

RORDAME'S comet was eleven days past perihelion when its coma was found to have decreased suddenly in diameter. It was seven months after perihelion passage that HOLMES' comet reduced to 29″ in apparent diameter; about a month previously — on Dec. 10, 1892, (*A. and A.-P.*, Vol. XII, p. 32),—its diameter across the nucleus was fully forty times as great. GALE'S comet passed perhelion on April 13, 1894. The table shows that marked and irregular changes in its diameter occurred after that date. These examples are far from confirming the general statement that the head of a comet *regularly* changes its diameter as it recedes from the Sun. Nor do they lend support to HERSCHEL'S suggestion, that the changes are optical rather than real. Their reality is evident, and they incur the suspicion that a more attentive study, even of ENCKE'S well-known comet, might reveal new facts relating to its variations, and they suggest the possibility that these variations may not be as closely related to the distances of the comet from the Sun as has been hitherto supposed.

EXTENSION TO THE COMA OF RORDAME'S COMET.

In all the earlier photographs there is a short and very faint extension to the coma in the position which would be occupied by a tail of the third type, according to BREDICHIN'S theory. Without at present entering into an extended account of this theory, it may be stated that it supposes the tails of this type to consist of matter having considerable density, and from various considerations, to fix ideas, suggests that it may be, and probably is, largely vapor of iron, with an admixture of the vapors of other elements having nearly the same molecular weights. Tails of this type are not of very frequent occurrence,

and on this account this faint extension possesses more than ordinary interest. No streamers such as compose the tail proper are observable in it, but their absence may be readily explained. Its shortness and faintness would render them inconspicuous; and, besides, if the particles composing it were in rapid movement,—and there is good reason for believing this to have been the case,—the resulting images would be blurred, and the individual character of the streamers lost. The presence of iron vapor in this comet was not detected by the spectroscopic observations. This, so far as it goes, is an item of negative testimony, but it cannot be regarded as having any considerable weight. This extension was very faint. The radiations from it may have been too feeble to have rendered the characteristic lines of its spectrum visible; and, moreover, the spectroscopic observations were made, not upon it, but upon the coma, and here the continuous spectrum would largely obliterate any very faint lines having their origin by reason of matter such as composed this extension.

The Streamers Composing the Tail.

We have already referred to the extent and brightness of the tail of this comet and of the fortunate situation in which it was placed with respect to the line of sight during the time of its greatest brilliancy, rendering it possible to obtain the most satisfactory visual and photographic views of it. We come now to consider some of its photographic peculiarities.

By the photographs, the tail was shown to be composed of numerous streamers, which presented very different appearances on the different nights. Usually a number of groups of them diverge from the central part of the coma and subdivide into many individual streamers before fading away or reaching the end of the tail. The central groups always contain the longest streamers, and the ones which present the greatest number of singularities. The streamers in the outer groups are generally short and straight. In the central groups they are long and often irregular. Sometimes they present a twisted appearance. This was especially the case on the evening of July 18th, when they had very much the appearance of the twisted forms produced by an electrical discharge in a magnetic field.* On this occasion the streamers proceeded from the coma in a single, very

* Some of the photographs of Swift's comet, 1892a, also show a twisted appearance in the tail. (See *Astronomy and Astro-Physics*, Vol. XII, page 205.)

compact bundle, from which the separate ones loosened as the distance from the head increased.

The streamers proceed from the central part of the coma, apparently directly from the nucleus, but it is not possible to be entirely certain concerning this. The late Mr. RANYARD has called attention to this point. In *Knowledge*, September 1, 1894, he says: "The streamers of the tail appear to issue from the center of the nucleus, and not from either side of the envelopes about the comet's head, as the drawings of some of the larger comets would lead one to suppose; but this may possibly be due to irradiation, which causes the bright nucleus and surrounding envelopes of the comet's head to appear larger than they really are." The concurrent testimony of a large number of experienced astronomers as to what they have seen in the case of the great comets leaves no doubt as to the general appearances of the features of these bodies. We may, however, with the best of reasons, conclude that even the most finished drawings which they have furnished us are only sketches, almost wholly wanting in detail and inaccurate in many respects. BOND'S many and beautiful drawings of DONATI'S Great Comet of 1858, contained in Vol. III of the *Annals of the HARVARD College Observatory*, and DE LA RUE'S fine drawings of the Great Comet of 1861, are examples, not to mention many others. These drawings furnish the most convincing proof that in these cases the tail sprung from the envelopes about the nucleus, and not from the nucleus itself. But they show the envelopes and the tail, in general, with a symmetry and smoothness manifestly accordant with the theory of cometary phenomena, and not with that irregularity and abruptness which has become so familiar since the appearance of photography in this line of work. Photographic irradiation has the effect mentioned by Mr. RANYARD, and especially in the case of the photographs of long exposure, such as were sent to him. But the photographs obtained with short exposures are not greatly affected by irradiation, and yet they point to the same conclusion as those of longer exposure. In this connection, it is needless to say that in the study of a point like this the original negatives have an advantage over any of their reproductions.

The groups of streamers are sometimes distinct, and the spaces between them quite free from luminous matter; dark spaces then separate them. These dark spaces are not constant in their positions; they change with the streamers. Sometimes

COMET RORDAME, JULY 15, 1893.

$8^h\ 45^m$ — $9^h\ 30^m$ P. S. T.

Photographed by W. J. Hussey, at the Lick Observatory.

they make a considerable angle with the general axis of the comet's tail, and at others they nearly coincide with it. According to the commonly accepted theory of the formation of the tails of comets, matter in an attentuated state is driven from the head of the comet by a repulsive force, and it is also subjected to the action of a repulsive force from the Sun, which drives it backward from the tail. The orderly development of a comet's tail, in accordance with this hypothesis, would lead to a figure more or less curved, having somewhat the appearance of what may be called a hollow curved cone, and it would be brighter near the edges than in the center along the axis of the tail. Many visual observations attest to appearances of this kind; but the photographs of RORDAME'S comet give very little, if any, realization of such a conical form, and these photographs are in this respect, I believe, entirely in accord with all the others which have been obtained of recent comets. The individual streamers cannot be seen by visual observations, and even the groups of them blend together to such an extent that they cannot generally be clearly distinguished. As a consequence of this, the dark space between two principal groups of streamers will in the case of the smaller comets, by being imperfectly seen, give the tail a hollow appearance, and, even with the comets of largest size, something of this effect will be produced. It would be highly interesting to know to what extent the hollow appearance of the tails of the great comets is due to this cause. It is, however, far from probable that it alone affords an adequate explanation.

CONDENSATIONS IN THE TAIL.

Among the conspicuous features exhibited in some of the photographs of recent comets are masses of luminous or illuminated matter constituting a part of the tail. They have been called *condensations*. They have occasionally been seen visually in the great comets, but such observations have been very rare. They were beautifully photographed by Professor BARNARD in SWIFT'S comet, in April, 1892, and in BROOKS' comet, in October, 1893. They were very conspicuous in some of my photographs of RORDAME'S comet, and are to be found in others. Condensations have also been photographed by several other astronomers at other observatories.

They are not constant features. They may be visible one day and invisible the next. They were conspicuous at times in the

comets named above, three of the brightest of which have appeared during the past three years. This indicates that they are not exceptional among cometary features, and suggests not only the possibility of their being more or less constantly present in those of the largest class. It is not unreasonable to suppose that they are simply the more dense aggregations of the matter which constitutes the tail, and that the streamers themselves would in all cases be found to consist of similar but less pronounced aggregations, if they could be observed under circumstances sufficiently favorable. That they have not been observed more frequently is to be attributed to the circumstances of their position and to inadequate means of observation.

THEORY OF COMET TAILS.

It is stated above that, according to the commonly accepted theory of the formation of the tails of comets, matter in an attenuated state is driven from the head of the comet by a repulsive force, and is also subjected to the action of a repulsive force emanating in the Sun, which drives it backward to form the tail. This theory has been brought to a high degree of perfection by the successive labors of many astronomers, particularly OLBERS, BESSEL, NORTON, and BREDICHIN. OLBERS' investigations* were incited by the phenomena of the Great Comet of 1811; BESSEL'S† by those of HALLEY'S comet on its return, in 1835; NORTON'S‡ by DONATI'S comet, in 1858, and COGGIE'S, in 1874. BREDICHIN'S investigations§ have included a careful study of a large number of comets.

According to this theory, the shape and position of the tail depend upon the motion of the comet and the effective intensity of the repulsive force. And, consequently, given the motion of the comet and the shape and position of its tail, it becomes possible to compute the effective intensity of the repulsive force. But the mode of action of this force enters into its expression, and we approach the unknown. We do not know absolutely the manner of its variation, whether it varies as the mass, or surface of the particle repelled, or how. There are many considerations which favor the view that the force is a case of electrical repul-

***Monatliche Correspondenz*, Vol. XXV, page 3.

†*Astronomische Nachrichten*, Bd. 13.

‡*American Journal of Science*, 2d Ser., Vol. 29, page 383, Vol. 32, page 54, and 3d Ser., Vol. 15, page 161.

§*Annales de l'Observatoire de Moscou.*

sion. This is the usual assumption. If this is the case, there is a surface action, the force being the same for equal surfaces of any kind of matter. This is equivalent to assuming the effective accelerating force to be proportional to the molecular weights of the substances moved, and a force acting in this way would produce different effects, according to the kind of matter upon which it acts. The matter having the least molecular weight would be driven most directly away from the Sun, the heaviest would trail along near the path of the comet, and that of intermediate weight would stream out in curves situated intermediate between these two positions. Thus the position of a comet's tail would become an index of the material composing it, and multiplicity of tails would indicate a complex chemical constitution.

From a study of the forms of a large number of comets, BREDICHIN has arrived at the following classification of their tails into three types:

I. Tails which are very straight and directed very exactly away from the Sun.

II. Tails which are considerably curved, being convex towards the direction of motion.

III. Tails which are short and strongly curved, situated almost in the path of the comet.

From a consideration of the ratios of the molecular weights of the various elements which the spectroscope has shown to exist in comets, he suggests, to fix ideas, that the tails of the first type may consist of hydrogen, those of the second type of hydrocarbon compounds, and those of the third type of heavy metallic vapors, such as iron, etc.

From the preceding statements it appears that the formation of a comet's tail depends upon a number of heterogeneous elements; the chemical constitution and physical condition of the matter composing the tail, as well as the nature of the repulsive force, and the geometrical form of the tail are all bound together by mutual relations. The spectroscope furnishes some information concerning the chemical constitution of these bodies; laboratory investigations on meteorites may furnish more; by photography the form and position of the tail may be accurately determined. But even with all this, not enough is known. From an analytical standpoint there are still a larger number of unknown quantities than there are equations of condition, and the solutions are, therefore, indeterminate. Something more

must be added by observation before this tangle of complex relations can be unraveled. Any independent data connecting the unknown quantities will be useful. The velocities with which the particles composing the tail recede from the head, if they can be obtained with sufficient accuracy, will enable a long step in the right direction to be taken. Two methods of obtaining these velocities suggest themselves; first, by measuring the motion in the line of sight spectroscopically, a thing which may be possible in the case of very bright comets, and, second, by measuring the displacements on a series of photographs taken with proper exposures and at short intervals of time. From some of the results already obtained by photography, it is highly probable that we now possess sufficient means to enable these velocities to be obtained, at least in the case of the brighter comets. In SWIFT'S comet, 1892, it was noted* that the condensations were receding from the head at a measurable rate, and it has been possible to make approximate estimates of the rate of

MOTION OF CONDENSATIONS IN RORDAME'S COMET.

On the evening of July 13, 1893, I obtained three photographs of RORDAME'S comet, two of which were taken with the CROCKER telescope — one with an exposure of six minutes (from $9^h\ 0^m$ to $9^h\ 6^m$), and the other of seventy minutes (from $9^h\ 10^m$ to $10^h\ 20^m$), P. S. T.

These negatives show the same condensations; on account of the short interval between the exposures, there can be no mistake of identification.† By a comparison of the position of the condensations in reference to the nucleus, it is easy to see that they are not fixed, but in rapid motion away from the head of the

* SWIFT'S Comet (a 1892). By A. E. DOUGLASS, *Astronomy and Astro-Physics*, Vol. XII, page 202.

† In *Astronomy and Astro-Physics*, Vol. XII, page 203, Mr. DOUGLASS states, in his article on SWIFT'S comet: "For purposes of measuring the velocity of recession from the head, eight points were identified, each point being found upon two plates, and their distances from the nucleus were determined. They may be subject to small errors, owing to the hazy outlines of the comet itself. Nevertheless, one case is subject to no uncertainty. It occurs on the plates of April 7th and 8th, when a slender, curved stem connects the head with a conspicuous and well-defined luminous mass at the base of the main tail."

I do not understand this statement. It is not clear to me whether the "one case" which "is subject to no uncertainty" refers to the *measurements of velocity* or to the *identification of condensations*. If the latter is meant, it would seem that the most certain identification of condensations made by Mr. DOUGLASS depends upon a comparison of plates of different dates—April 7th and 8th. *Such an identification would be extremely uncertain*, and, in the present state of our knowledge, would have no value, unless confirmed by the plates taken between the two dates, thus forming a practically continuous record.

comet. If the condensations were clearly defined, it would be easy to measure their distances from the nucleus in the two negatives, and then to calculate their rate of recession from it. With these negatives it is not possible to make the necessary measurements with very satisfactory exactness. The nucleus is practically concealed in the photographs by the dense coma surrounding it. The rapid relative motions of the condensations caused them to be photographed as trails, thus giving blurred images; and, moreover, this effect is not present to the same extent in the two negatives, on account of the disparity in the times of exposure. On these accounts it is impossible to determine the exact points upon which the measurements should be made, and the results are correspondingly uncertain. This uncertainty would be materially decreased if the negatives were of equal exposure, and that of only sufficient duration to give distinct images of the condensations.

Measurements have been made on three condensations situated at distances of $1^{\circ}.87$, $3^{\circ}.66$, and $5^{\circ}.88$ from the nucleus, giving respectively velocities of forty-four, fifty-two, and fifty-nine miles a second. In the computation of these velocities the effect of projection and of the difference of differential refraction have been included. The second condensation is more determinate than the others, and its velocity is, therefore, entitled to a greater degree of confidence.

The lowest of these velocities corresponds to nearly 4,000,000 and the highest to somewhat more than 5,000,000 miles a day. Enormous as these velocities are, they do not exceed those which are to be expected from the consideration of certain cometary phenomena. For example, the rapid changes in the direction of their tails at the time of perihelion passage and the sudden changes in the forms of the tails predicate enormous velocities.

Such velocities as those stated above are highly significant. They must be taken into account in considering the remarkable changes which take place in the forms of the tails of comets as exhibited by their photographs. On their account the photographs are to a certain extent inaccurate and misleading. During the time of exposure, and especially in the case of a long one, the condensations, and very likely all the other forms which go to make up the tail, move an appreciable angular distance, and are consequently photographed as trails. This is a result that is

inevitable. It cannot be wholly overcome by any change in the manner of using the telescope. Exposures of short duration will avoid a part of the difficulty, by making the trails shorter, but another and perhaps more serious difficulty will be introduced. With short exposures, the negatives will be thin, wanting in detail, and generally unsatisfactory. The only practical course is to keep in view the probable velocities of motion and to allow for their effect in the interpretation of the photographs.

In consequence of their motions, the condensations trail and their photographic representations are blurred and indistinct. Details relating to form are lost, dimensions in the direction of motion exaggerated, and intensities correspondingly diminished. The fainter condensations fail to make a definite impression; they are blended with the streamers, and the streamers are blurred and intensified by them. Photographs of short exposure naturally show the condensations nearly in their true proportions, and from such photographs it appears, in the case of RORDAME'S comet, that they are generally not of large dimensions. Their trailing satisfactorily explains why they are so conspicuous in the photographs of long exposure and at the same time invisible to the eye.

In RORDAME'S comet the condensations were moving with an accelerated velocity. This is in accordance with cometary theory. Even at the measured velocities, the condensations would have traversed a distance equal to the length of the brighter portion of the tail in less than a day. It seems probable that those observed on July 13th traversed the entire length of the tail, or had become entirely dissipated in less than this time. They are not to be found on the photograph of the preceding night, nor on those of the following night.

If like velocities can be established in the case of other comets, it is evident from the preceding paragraph that the streamers and condensations which form the tail one day cannot be assumed to be the same as those which form it on the next. To establish the identity of condensations, streamers, and groups of streamers, observed on successive days, requires either a practically continuous record for the intervening time or a tolerably complete acquaintance with the laws of force in accordance with which the changes take place. Neither of these requirements have been sufficiently supplied. Notwithstanding the manifold labors of many eminent astronomers, cometary theory has not yet reached that stage of

COMET RORDAME, JULY 16, 1893.

$9^h\ 00^m$ — $10^h\ 00^m$ P. S. T.

Photographed by W. J. HUSSEY, at the LICK Observatory.

its development which enables us to account for the capricious changes which have been so many times observed. No complete photographic record has been obtained of any comet, and, manifestly, it cannot be obtained by the work of a single observatory. That we should have such a record of the important comets which are favorably situated for photographic observation is a desideratum.

THE QUESTION OF ROTATION.

The considerations of the last paragraphs have an important bearing on the general question of the rotation of the heads of comets. It is very natural that this question should have arisen, and that there should be numerous references to it in the cometic literature of this century. In no comet has rotation been clearly established. BREDICHIN summarily disposes of that part of DUNLOP'S observations of the Comet of 1825, IV, "On the changes which take place in the figure of the tail, tending to establish the existence of a rotation round its axis,"* by saying, "these attempts have no value, and only show that DUNLOP, although a skillful observer, had very little acquaintance with the principles of mechanics."

BESSEL carefully considered the phenomena of HALLEY'S comet on its return in 1835,† and found the evidence somewhat more largely in favor of rotation about an axis lying in the plane of the orbit than about one perpendicular to this plane. These researches of BESSEL form an interesting section of his classic memoir, but they cannot be regarded as having proved or disproved the rotation of the head of this celebrated comet.

NORTON'S investigations in this direction were incited by the "columnar structure‡ of the tail" of DONATI'S comet. In this connection he says:§ "An interesting result of the investigation is that the alternate bright and dark bands so distinctly seen to traverse a certain portion of the tail of DONATI'S comet, in nearly parallel directions, on the evening of October 10th, had each the position of the line connecting particles which started from the region of the nucleus at a certain previous date and at the same

* BREWSTER'S *Edinburgh Journal of Science*, 1827; *Annales de l'Observatoire de Moscou*, Vol. VIII, 1, pages 86 and 95.

† *Astronomische Nachrichten*, Bd. 13.

‡ According to BOND, the observations on the "columnar structure of the tail" of DONATI'S comet were quite discordant. (*Annals of the Obseraatory of* HARVARD *College*, Vol. III.)

§ *American Journal of Science*, 2d Ser., Vol. 29, page 81.

instant of time. They accordingly find their natural explanation in corresponding alternations in the quantity of nebulous matter given off simultaneously from the nucleus. The most probable cause of such alternations of discharge that can be conjectured is that the nucleus turns about an axis, and so presents periodically different sides to the Sun, which were unequally influenced by his inciting action. If this be the true explanation of the phenomenon, we have in the observed distance between contiguous bright bands the means of determining the period of rotation; or, at least, the shortest interval of time in which the rotation can be completed. If we take these distances at 1°, the period of rotation comes out twenty-four hours."

The photographs of recent comets afford illustrative material which renders it very probable that the alternation of bright and dark bands which produced the columnar structure in the tail of DONATI'S comet were nothing else than streamers of extraordinary brightness and the dark spaces between them. This is rendered the more probable by the fact that the streamers, as shown by the photographs, sometimes lie obliquely to the axis of the tail, as was the case with the bands observed in DONATI'S comet. On this account we are inclined to regard them in a somewhat different light from that in which NORTON viewed them, in so far, at least, that instead of each streamer being composed of particles which left the region of the nucleus at the same instant of time, that it must have been composed of those leaving that region at very different times. If we accept the streamers as affording an explanation of the banded or columnar appearance of the tail, we at once remove not only the basis of Professor NORTON'S calculation of the period of rotation, but also, as far as can be judged from the records of the phenomena of these streamers, *nearly* all evidence whatever of rotation.

Professor BARNARD has recently remarked the changes in the relative brightness of the component parts of SWIFT'S comet, as shown by its photographs, and states that it "would almost suggest a rotation of the tail about an axis through the nucleus."* The well-known rapid changes in the appearance and positions of the streamers and the entire absence of definite knowledge as to the order in which these changes occur, and of the conditions producing them, forbid us hastily assuming changes of brightness as indications of rotation. The changes in the positions of the

* *Astronomy and Astro-Physics*, Vol. XI, page 338

streamers, if they should be continuously observed, might possibly afford undoubted evidences of rotation and the data by means of which the period could be deduced, but it does not seem at all probable that this can be done from photographs taken at intervals of twenty-four hours or more.

If the head of a comet is a rotating body, the streamers emanating from it will have their forms in space determined by the circumstances of their projection and of the rotation. It is easy to see that the form of a streamer emanating from a given point in the head of a rotating comet will, in general, be a spiral of double curvature; the orbits, however, of the individual particles composing the streamer being hyperbolas. In some photographs there is abundant evidence of such spiral motion, especially in the case of streamers which issue from the center of the comet's head, and form the central portions of its tail. If the twisting of the streamers be taken as evidence of rotation, which may be a rather hazardous assumption in the present state of our knowledge, it will be necessary to explain why some are twisted and others are not in the same photograph, and why the twisting is more extensive on some occasions than on others.

If we assume that the head of a comet, or, at least, the denser portion of it, is merely a large aggregation of meteoroids with their attendant atmospheres, and, further, that the meteoroids are not uniformly distributed, but grouped in "swarms," it will not be difficult to imagine such conditions of revolution as would fully account for most, if not all, of the individual peculiarities of the streamers and groups of streamers, and, at the same time, be free from requiring a permanency in their forms and positions. In this case, however, we should not have a rotation of the comet, but revolution of its component swarms of meteoroids.

Curved and Broken Streamers; Encounter with Extraneous Matter.

An interesting phenomenon is the congruent bending of adjacent groups of streamers, it being often the case that a deflection in the components of one group is accompanied by a corresponding deflection of nearly equal magnitude in an adjacent one. This sometimes occurs in places where the groups of streamers are widely separated by clear spaces and at great distances from their common origin.

More or less abrupt bends also occur in single groups of

streamers. These, of course, are the more conspicuous when they occur in the larger groups. The principal group in the tail of SWIFT'S comet, on April 6, 1892,* was abruptly bent near the comet's head. Several similar bends occurred in the larger groups of streamers in the tail of RORDAME'S comet, on July 15, 1893.

At times, there are also breaks in the streamers. One of the principal groups in RORDAME'S comet, on July 12, 1893, was nearly discontinuous within a degree of the nucleus; nearer and further from the nucleus this group was strong. Extreme confusion reigned in BROOKS' comet, on October 21 and 22, 1893. On the first of these dates, the tail as a whole was curved in an unusual manner, being roughly sinuous, and, therefore, standing in marked contrast to that form which cometary theory prescribes; *condensations were numerous* and the streamers generally were much disturbed and confused. On the 22d, the tail was nearly straight; it was also very much shattered, one fragment being entirely detached. Professor BARNARD'S photographs of this comet for these dates are reproduced in *Knowledge*, February and May, 1894. In his account of his photographs he says:

"The tail now [October 21st] presented the aspect of a torch streaming in the wind. The appearance was precisely what we should expect had the comet's tail, in its flight through space swept across or through some medium dense enough to break up the tail. I cannot see how any one, comparing this with the picture of the 20th, can escape the conclusion that the tail did actually encounter a disturbing medium which shattered it. This theory is, I think, further upheld by the third of these pictures taken on the following morning [October 22d], where the tail hangs in cloudy masses, like the broken train from a locomotive. In the last picture a large fragment is actually torn off and completely separated from the end of the tail. In the second photograph [October 21st] the entire comet was brighter, as if the disturbance had added to its light, as also seems to have been the case with the third photograph, on October 22d; for its exposure was much shorter, as flying clouds were obscuring the sky a considerable portion of the time."

The view presented in this quotation has, naturally enough,

* Professor BARNARD'S photograph of this comet for this date has been published in *Knowledge*, Dec. 1892, and in third edition of CLERKE'S *History of Astronomy During the Nineteenth Century*.

not passed without criticism. As Mr. HARRY PROCTER says,* it is "more probable that the irregularities in the tail are due to irregularities in the quantity of matter streaming away from the nucleus, as well as due to changes in the direction in which the streams of matter are driven forth from the head of the comet," than that they are due to the resistance of extraneous bodies. It is undeniably true that the matter composing the tail of a comet is often emitted in an irregular manner. There is the amplest evidence of this in the photographs of recent comets. The existence of condensations proves it. It is also true that the streams of matter composing the tail proceed from the comet's head in very different directions at different times; moreover, they change with a rapidity which renders it impossible to identify with certainty those of one day with those of the next. The photographs also afford ample evidence of this. With these facts in mind, it is not difficult to imagine such variations in the quantity of matter emitted from the comet's head, and of such differences in the directions of emission at different times, to account fully for all those peculiarities in the forms of the tails of comets which have given rise to the doctrine of an encounter of the comet with a disturbing medium — a doctrine which, it is needless to say, has very little in its favor.

LELAND STANFORD JR. UNIVERSITY, May 27, 1895.

ADDENDUM.

After the foregoing article was in the hands of the printer, I received from Dr. BREDICHIN his paper entitled "*Mouvement des substances émises par les comètes,* 1893, II, *et* 1893, IV.†

The portion of his paper devoted to comet 1893, II (comet RORDAME), is based upon a letter that I sent him, January 28, 1895, as follows:

"You may be pleased to know that from a study of some of the photographs which I obtained of Comet RORDAME, I have been able to determine approximately the rate at which 'condensations' in the tail are receding from the nucleus. On July 13, 1893, G. M. T., about seventeen hours, a condensation of $3^{\circ}.7$ from the nucleus was receding at an hourly rate of not less than 400,000 miles.

* *Knowledge*, March, 1894, p. 63.

† *Bulletin de l'Académie Impériale des Sciences de St. Pétersbourg* (May, 1895).

"I have a paper in preparation, which will be published shortly, and I shall be pleased to send you a copy when it is ready."

I hasten to express my sincerest regret that this letter furnished Dr. BREDICHIN an incorrect datum; the velocity given in it is too large. The error was introduced in the calculation by two figures being inadvertently interchanged. With the velocities given in the foregoing paper, which, it is believed, are near the true ones, the results are much more nearly in accordance with those prescribed by cometary theory, being approximately twenty-five per cent. larger than we should expect for hydrogen — the element having the lowest known molecular weight.

The velocities given in the foregoing paper have been derived from measurements of the original negatives. These measurements were made on the measuring engine belonging to the LICK Observatory. On each of the two negatives of July 13, 1893, the distances from the nucleus to the condensations situated at $1^{\circ}.87$, $3^{\circ}.66$ and $5^{\circ}.88$ from it, were measured, and the differences of the results taken. These differences are 0.062, 0.071 and 0.081 inches respectively. These differences represent the motion of the condensations away from the nucleus in the mean interval between the exposures. This interval is forty-two minutes, the middle of the first exposure being $9^{h}\ 3^{m}$, and of the second, $9^{h}\ 45^{m}$, P. S. T.

From measurements of photographs of the stars, I have found the equivalent focal length of the CROCKER telescope to be 30.82 inches. The scale of the photographs is, accordingly, one inch $= 1^{\circ}.86$. The distances 0.062, 0.071 and 0.081 inches correspond, therefore, to angular movements of $415''$, $475''$ and $542''$, respectively. These values are too small, on account of being affected by the difference of differential refraction for the times of the two exposures. On this account, they must, respectively, be increased by $34''$, $48''$ and $54''$, giving $449''$, $523''$ and $596''$.

The comet's distance from the Earth was 44,377,000 miles — the logarithm of its distance in astronomical units being 9.67916. The tail of the comet was straight, and I have assumed that it coincided with a line through the Sun and the nucleus of the comet. This line, at the time under consideration, made an angle of $60^{\circ}\ 10'$ with the line of sight.

With these data, the velocities which I have obtained for the

three condensations are 44.2, 51.5 and 58.7 miles per second; or, expressed in astronomical units, the mean distance of the Earth from the Sun being the unit of distance, and 58.13244 mean solar days the unit of time, they are, respectively, 2.389, 2.783 and 3.171.

The theoretical velocity for tails of the first type, for the position of the second condensation, is 2.27, instead of 2.78 as given above.

As has been previously stated, the second condensation was more determinate than the others, and its velocity is accordingly entitled to a greater degree of confidence. Its velocity may be somewhat too small. I do not think it is too large.

Dr. BREDICHIN, assuming the velocity I sent him—400,000 miles an hour,—has computed the corresponding value of $1-\mu$, and obtained 247. In this μ is the effective acceleration of the Sun at the unit of distance. From his previous investigations, the definitive value* of $1-\mu$, for tails of the first type—which are supposed to consist of hydrogen—is 17.5.

With the same data that he used, but with the velocity given in this paper, I have found $1-\mu$ to be 36, or about twice as great as for the first type. According to Dr. BREDICHIN'S theory, this value of $1-\mu$ corresponds to a substance having a molecular weight only half as great as hydrogen.

June 22, 1895.

DESCRIPTION OF A NEW CASSEGRAINIAN TELESCOPE, EQUATORIALLY MOUNTED, HAVING AN EQUIVALENT FOCAL LENGTH OF TWO HUNDRED AND FIFTY FEET.

By J. M. SCHAEBERLE.

For obtaining the best astronomical photographs, the reflecting telescope should possess a great advantage over the refractor, for only by reflection can all the rays—both visible and invisible—of the spectrum, coming from a celestial object, be brought to a common focus.

With one or two exceptions, but little has been done in the

* *Annales de l'Observatoire de Moscou*, 2d Series, Vol. I, 1, page 22.